

OVERVIEW & OBJECTIVES

As an asteroid descends toward Earth, it deposits energy in the atmosphere through aerodynamic drag and ablation. Asteroid impact risk assessments rely on energy deposition estimates to predict blast overpressures and ground damage that may result from an airburst, such as the one that occurred over Chelyabinsk, Russia in 2013. The rates and altitudes at which energy is deposited along the entry trajectory depend upon how the bolide fragments, which in turn depends upon its internal structure and composition. In this work, we have developed an analytic asteroid fragmentation model to assess the atmospheric energy deposition of asteroids with a range of structures and compositions. The modeling approach combines successive fragmentation of larger independent pieces with aggregate debris clouds released with each fragmentation event. The model can vary the number and masses of fragments produced, the amount of mass released as debris clouds, the size-strength scaling used to increase the robustness of smaller fragments, and other parameters. The initial asteroid body can be seeded with a distribution of independent fragment sizes amid a remaining debris mass to represent loose rubble pile conglomerations, can be given an outer regolith later, or can be defined as a coherent or fractured monolith. This approach enables the model to represent a range of breakup behaviors and reproduce detailed energy deposition features such as multiple flares due to successive burst events, high-altitude regolith blow-off, or initial disruption of rubble piles followed by more energetic breakup of the constituent boulders. These capabilities provide a means to investigate sensitivities of ground damage to potential variations in asteroid structure.

FRAGMENT-CLOUD MODEL (FCM) APPROACH

INITIAL ASTEROID STRUCTURE

- Initial asteroid structure defined with a distribution of discrete fragments and a mass of debris particulates
- Initial aerodynamic strength for the overall structure defines pressure at which initial disruption occurs.
- Strengths of the constituent fragments can be defined directly, given a uniform value, or assigned based on relative sizes using a Weibull-like scaling.
- Can represent broad range of structural characteristics, from rubble piles to monoliths.

ENTRY FLIGHT INTEGRATION

- Single-body meteor equations of motion and ablation [1] using fixed altitude steps:

$$\begin{aligned} dm/dt &= -0.5\rho_{air}v^3A\sigma \\ dv/dt &= \rho_{air}v^2AC_D/m - g\sin\theta \\ d\theta/dt &= (v/(R_E+h) - g/v)\cos\theta \\ dt &= dh/v\sin\theta \end{aligned}$$

- Flight integration is performed for initial body and each fragment and cloud component.

DISCRETE FRAGMENTATION

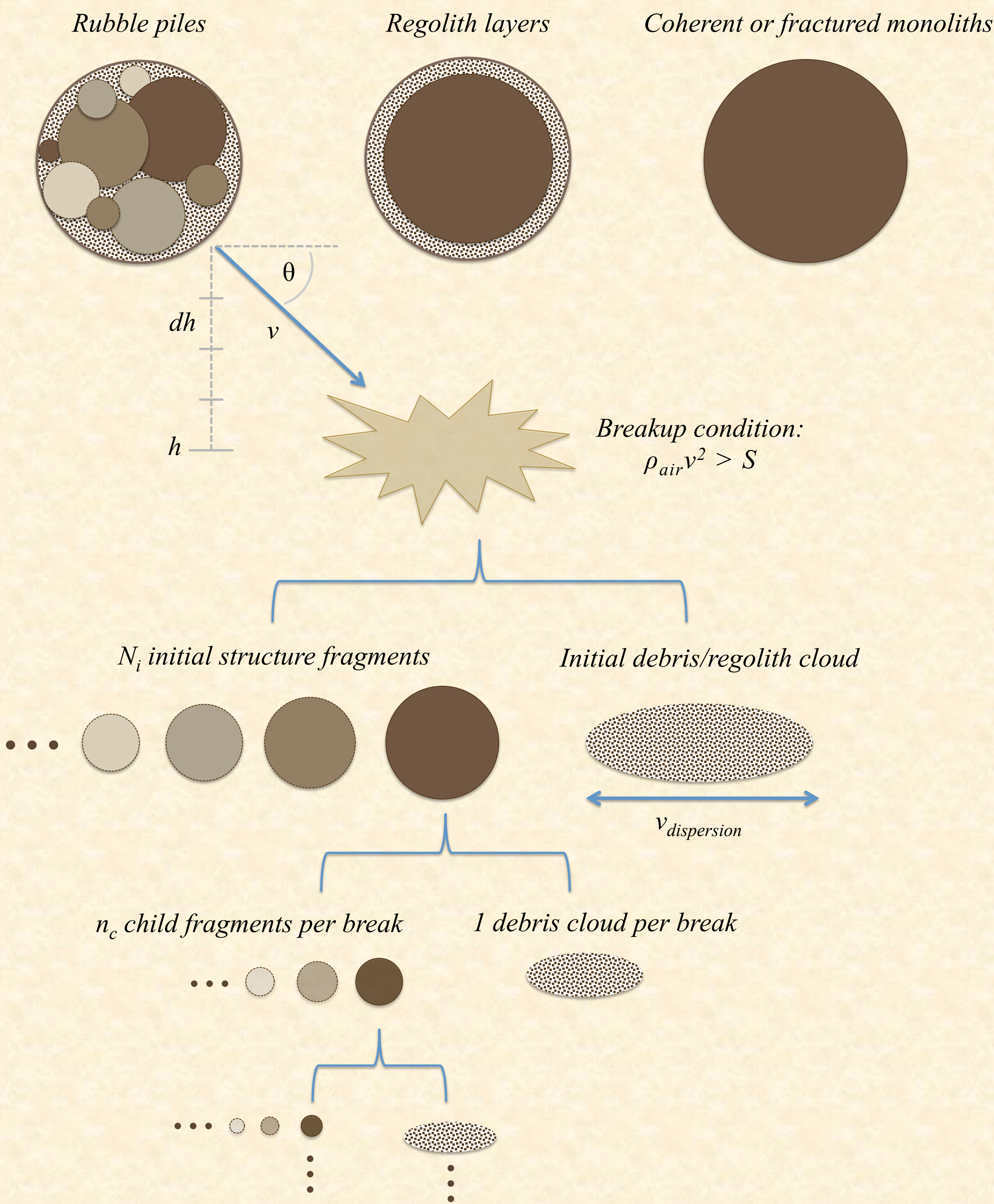
- After disruption of the initial structure, each discrete fragment undergoes successive fragmentation, breaking each time the pressure exceeds its strength parameter [2]: $\rho_{air}v^2 > S$
- Each break produces a given number of independent fragments and a debris cloud of a given mass fraction.
- Fragments can be uniform or given a mass distribution.
- The strength of each child fragment increases based on its size relative to the parent fragment and a strength scaling exponent input α : $S_f = S_p(m_0/m_f)^\alpha$
- Based on triggered progressive fragmentation approach [3].

DEBRIS CLOUDS

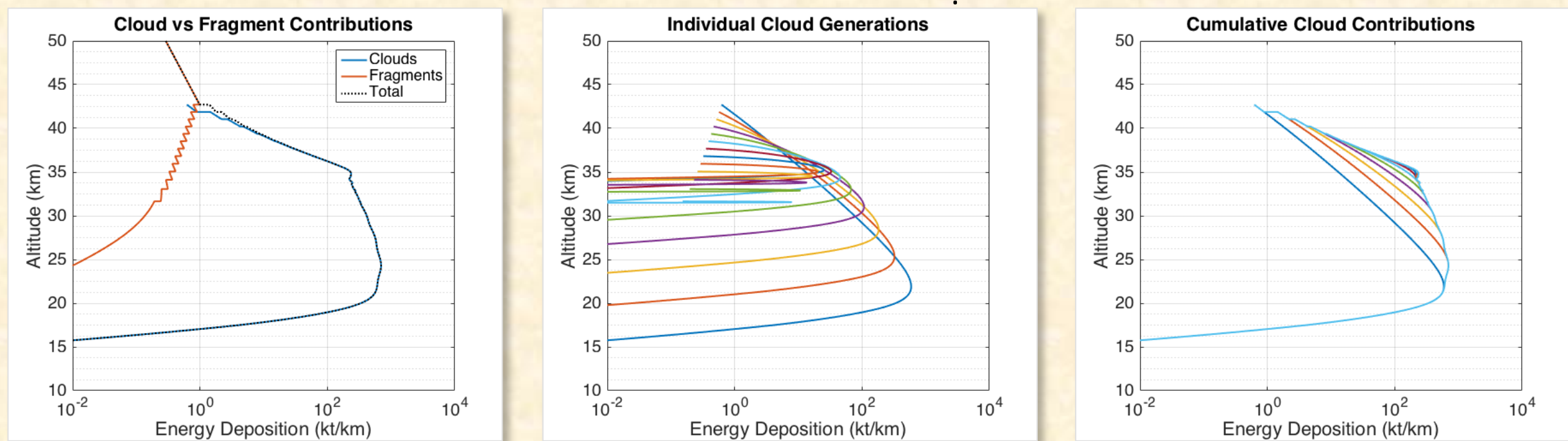
- Debris clouds are treated as single, aggregate masses that disperse and slow under a common bow shock.
- Cloud cross-sectional areas spreads laterally with a dispersion velocity: $v_{disp} = v_{cloud}(C_{disp}A_p\rho_{air}/\rho_{cloud})^{1/2}$
- Flight integration continues, with drag and ablation increasing with the growing surface area.
- Based on “pancake” model approach [2]

ENERGY DEPOSITION

- Energy deposited in the atmosphere through drag and ablation is computed as the total change in kinetic energy of all fragment and cloud components, per unit altitude (kilotons per kilometer).
- Cloud masses drive the overall energy deposition.
- Discrete fragmentation enables variation in the sizes and numbers of clouds deposited at different altitudes.
- Combination of cloud and fragment components with variable input parameters enables model to reproduce a wide range of breakup behaviors and resulting energy deposition features.



Fragment and cloud contributions to energy deposition for a sample 50 m asteroid, beginning as a simple monolith and breaking into two even sub-fragments and 50% cloud mass with each successive fragmentation



SENSITIVITY TO FRAGMENTATION PARAMETERS

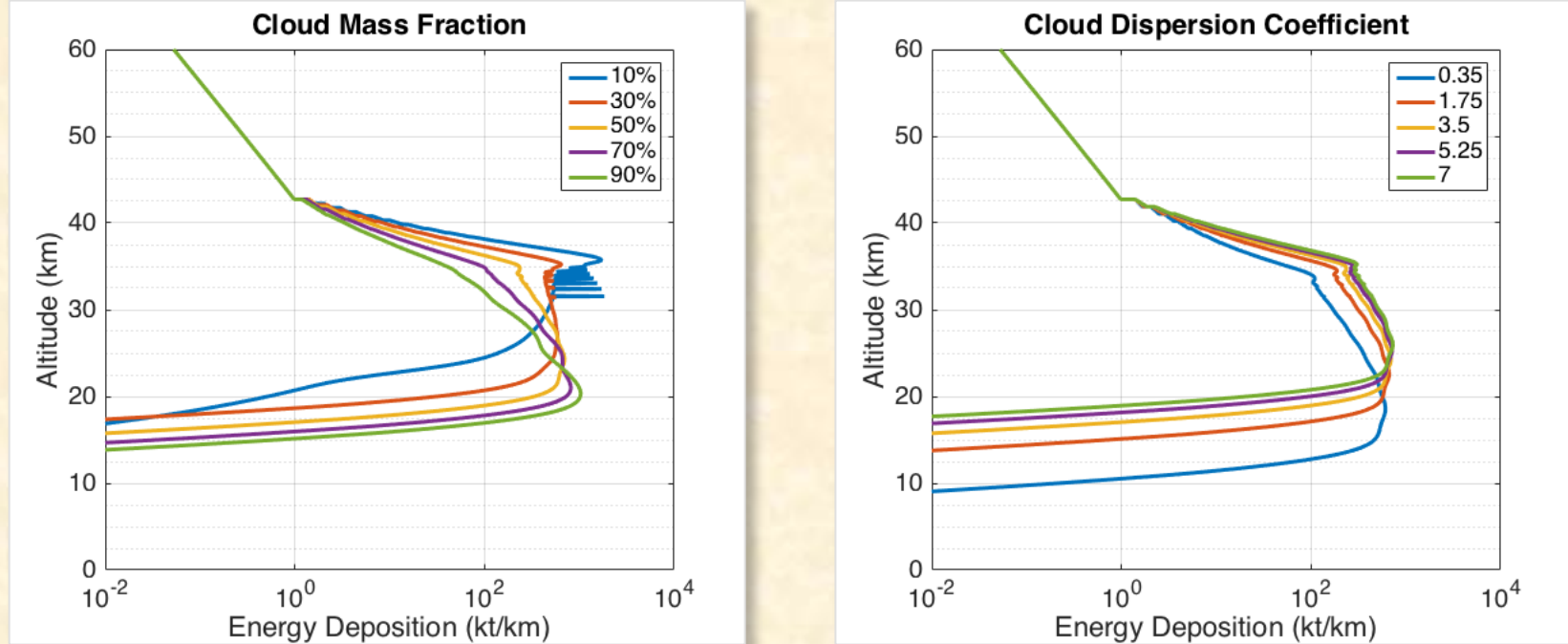
We are performing sensitivity studies investigating how the model’s fragmentation parameters affect energy deposition trends and features. These studies vary a single fragmentation parameter at a time while holding the others at constant baseline values.

Asteroid parameters: 50 m diameter, 2.5 g/cc, 20 km/s, 45° entry angle.

Baseline fragmentation parameters: 50% cloud mass per break, cloud dispersion coefficient 3.5, 2 even fragments per break, 1 MPa initial aerodynamic strength, strength scaling $\alpha=0.1$.

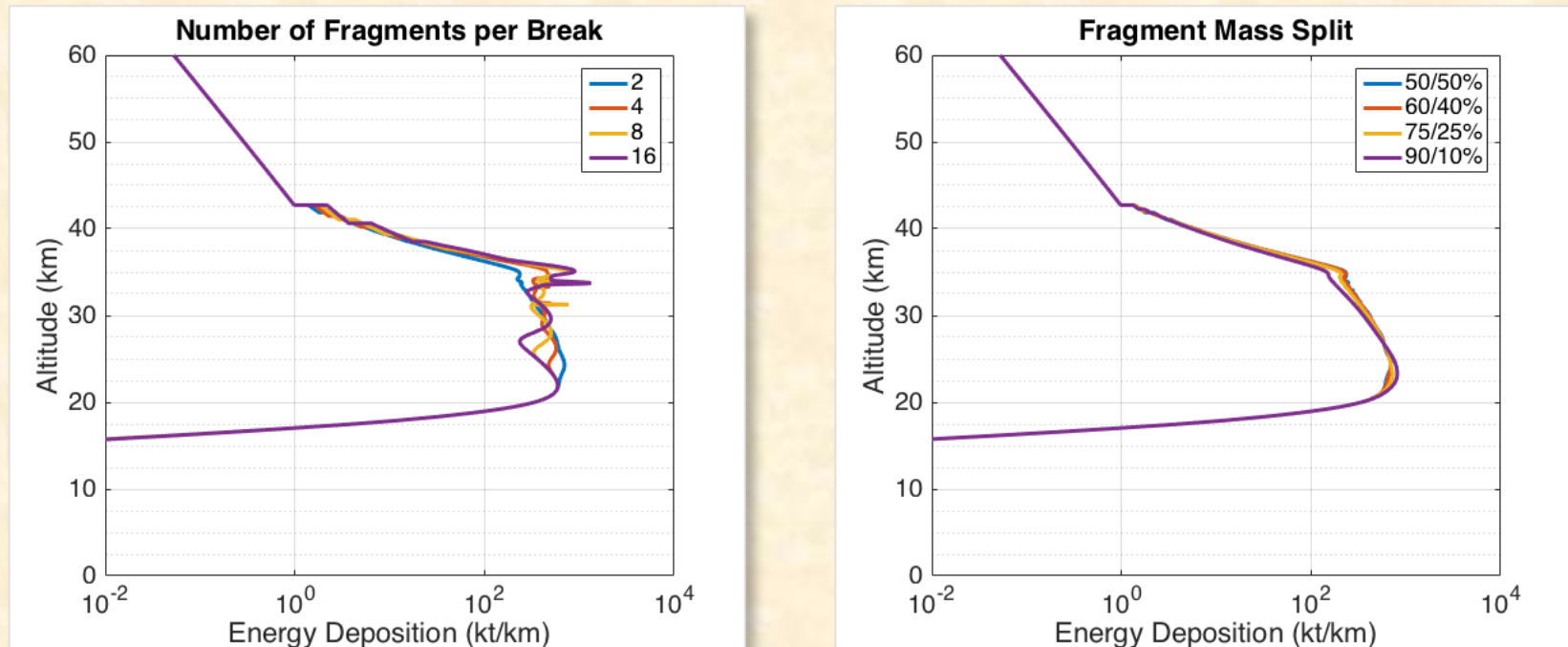
Cloud Mass & Dispersion

- Cloud mass affects whether the energy deposition peaks sharply at the top of the flare or more gradually near the bottom of the flare.
- Cloud dispersion coefficient affects the width of flares dominated by moderately large clouds.



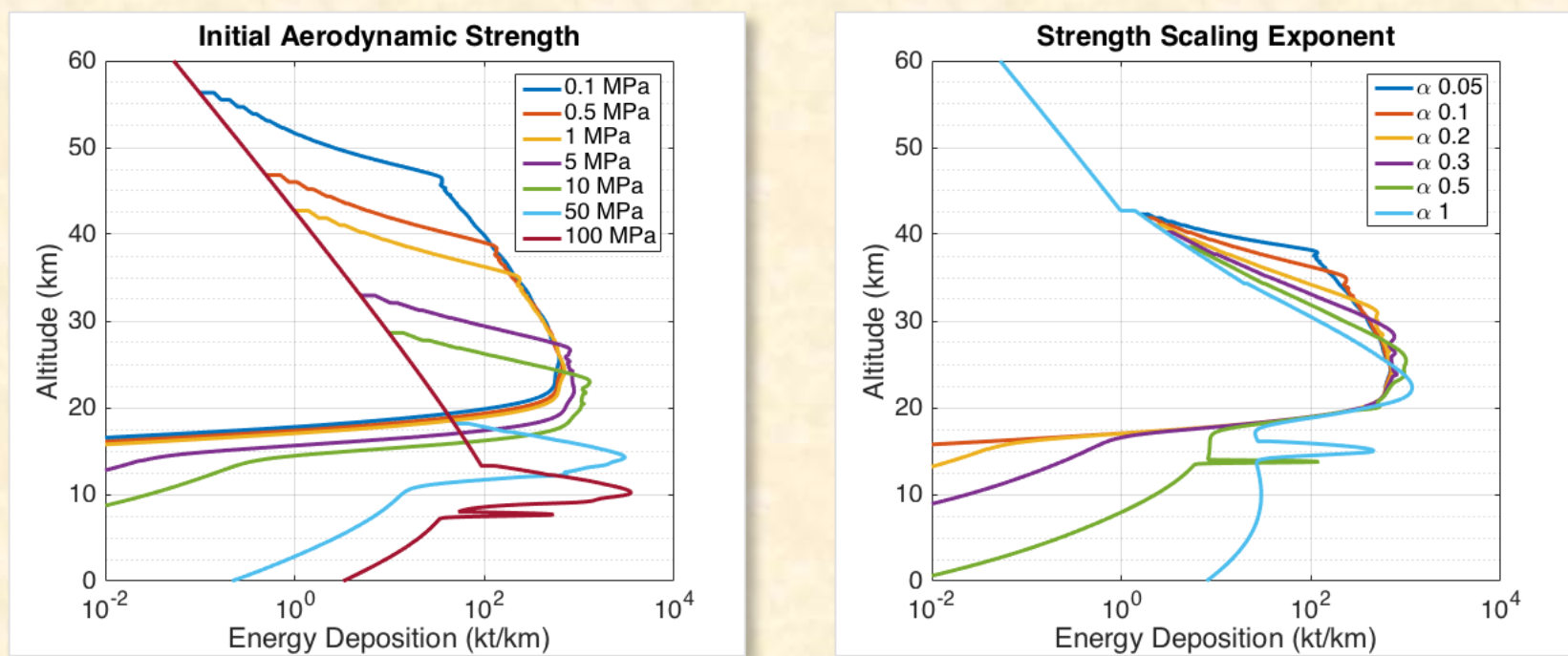
Fragment Numbers & Mass Distributions

- Fragment numbers and sizes influences energy deposition by dividing the deposited debris into smaller debris clouds.
- Large initial debris clouds tend to dominate overall energy deposition more than specific fragment splits.



Initial Aerodynamic Strength & Fragment Strength Scaling

- Strength parameters affect the width of the main flare by altering the altitude and slope of its upper edge.
- The main flare peaks and dissipates around the same altitude over a large range of strength parameter values.

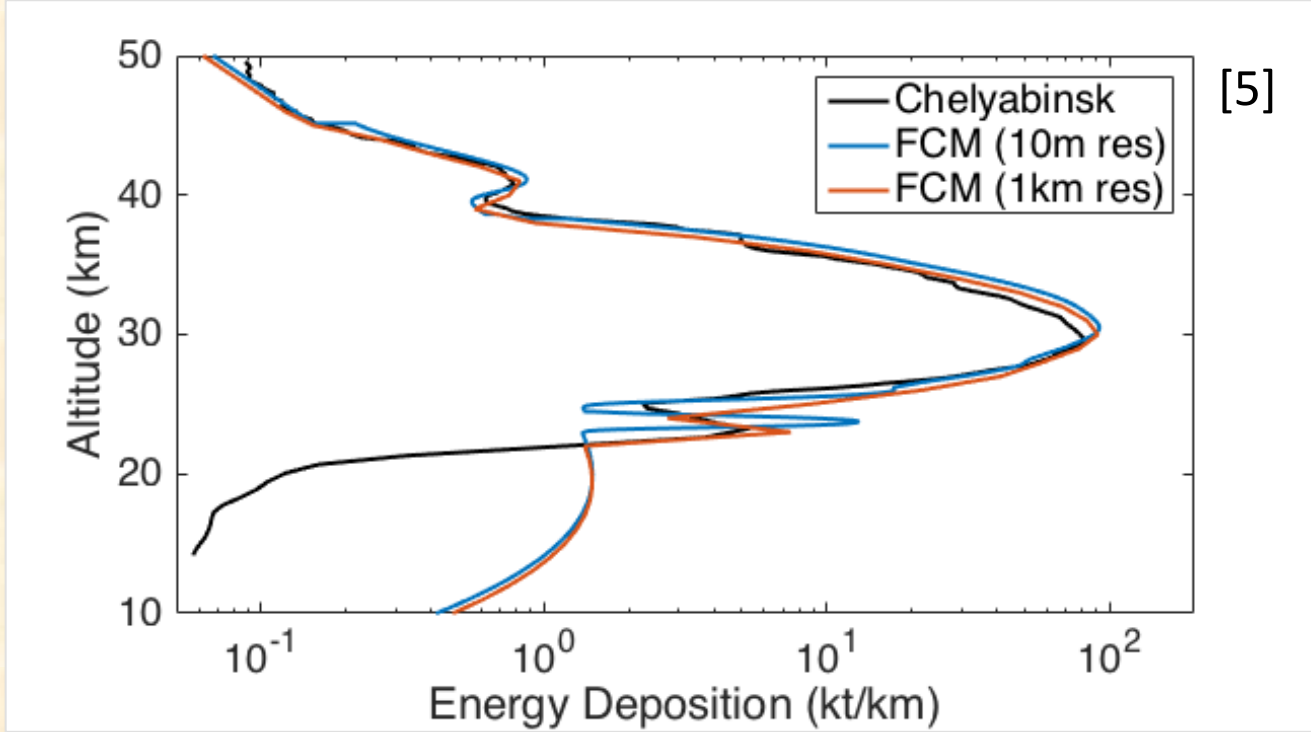


OBSERVED METEOR COMPARISONS

We have generated preliminary energy deposition matches to several observed meteor entries, exploring how different structure and fragmentation parameters can reproduce a range of observed features.

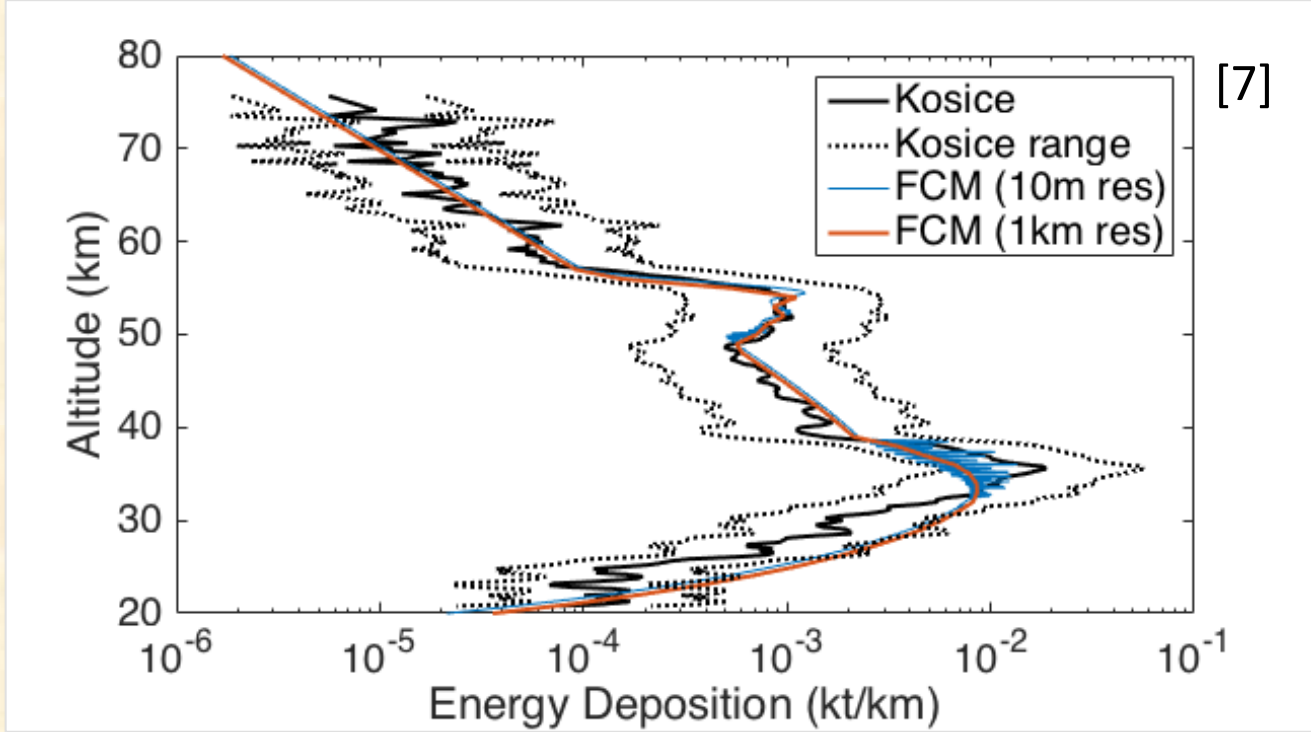
Chelyabinsk Meteor

- 19.8 m diameter, 3.3 g/cc, 5775 kg, 19.16 km/s, 18.3° [4].
- 0.2% regolith/debris mass released to produce small upper flare.
- Initial rubble fragments: 60/30/10% mass splits, strengths ~1.6-2 MPa.
- Successive fragmentation into 80% cloud mass and 4 fragments with mass splits of 40/30/20/10% and high strength scaling $\alpha=0.6$.



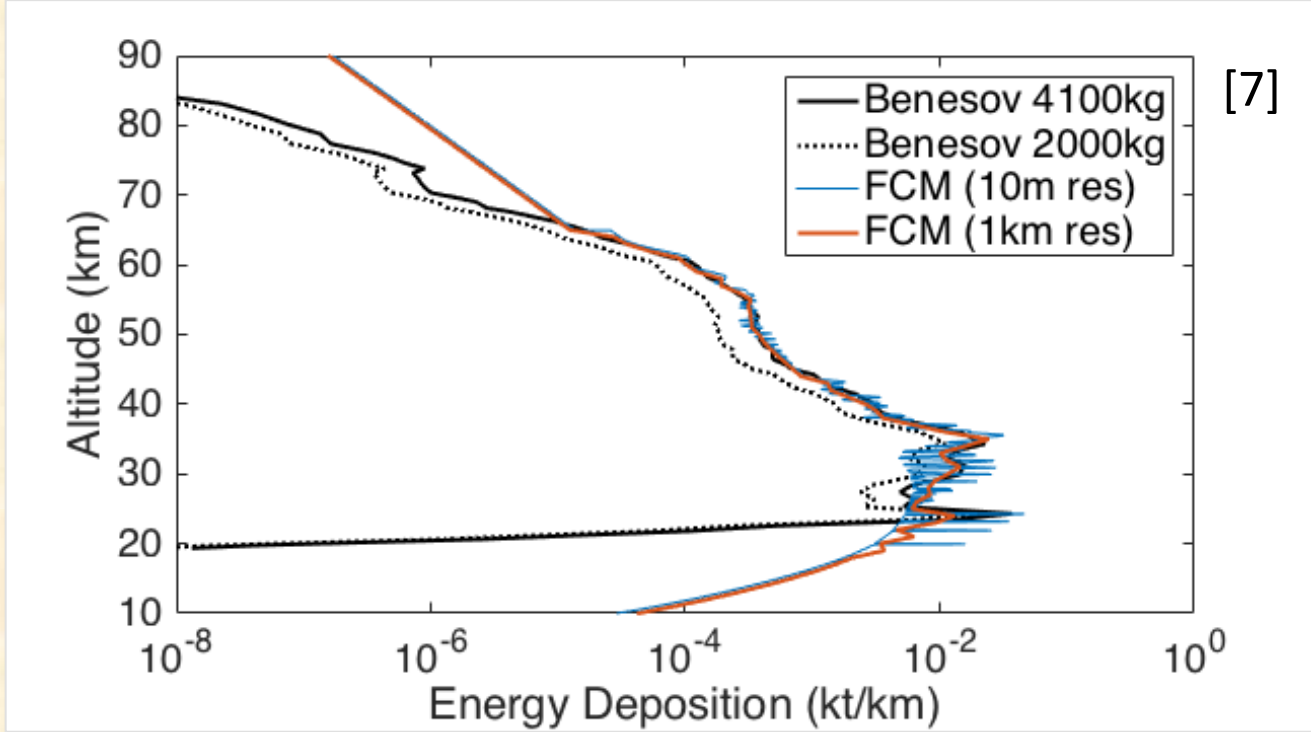
Košice Meteor

- 1.5 m diameter, 3500 kg, 2 g/cc, 15 km/s, 60° [6] .
- Initial fracture into ~60 fragments with 0.3-9% mass splits and size-dependent strengths ($\alpha=1.8$) 0.05-20 MPa.
- Successive fragmentations into 3% cloud mass and 2 fragments with 60/40% mass splits and $\alpha=0.12$.



Benešov Meteor

- 1.3 m diameter, 4000 kg, 3.2 g/cc, 21 km/s, 81° [8] [9].
- Initial fracture into 14 primary fragments with 0.1-30% mass splits, plus 100 very small fragments (0.002% each), with strengths 0.03-18 MPa.
- Successive fragmentations into 20% cloud mass and 2 fragments with 80/20% mass splits and $\alpha=0.3$.



ACKNOWLEDGEMENTS & REFERENCES

This work was performed as part of the Asteroid Threat Assessment Project at NASA Ames Research Center, funded by NASA’s Planetary Defense Coordination Office. REFERENCES: [1] Opik, E. J., Physics of Meteor Flight in the Atmosphere, Interscience, New York, 1958. [2] Hills, J. G., Goda M. P., The Fragmentation of Small Asteroids in the Atmosphere, The Astronomical Journal (105-3), pp. 1114-1144, 1993. [3] ReVelle, D. O., Recent Advances in Bolide Entry Modeling: A Bolide Potpourri, Earth, Moon, and Planets (95), pp. 441-476, 2005. [4] Popova, O. P., et al., Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization, Science (342), p. 1069, 2013. [5] Brown, P. G., et al., A 500-kiloton Airburst over Chelyabinsk and an Enhanced Hazard from Small Impactors, Nature (503-7475), pp. 238-241, 2013. [6] Borovička, J., et al., 2013. The Košice Meteorite fall: Atmospheric Trajectory, Fragmentation, and Orbit. Meteoritics & Planetary Science 48, p. 1757 – 1779. [7] Stokan, E., Brown, P. G., Energy Deposition Curves for Benešov and Kosice Meteors, personal communication. [8] Ceplecha, Z., ReVelle, D. O., 2005. Fragmentation Model of Meteoroid Motion, Mass Loss, and Radiation in the Atmosphere, Meteoritics & Planetary Science 40, p. 35 – 54. [9] Borovička, J., et al., 1998. Bolides Produced by Impacts of Large Meteoroids into the Earth’s Atmosphere: Comparison of Theory with Observations. Astronomy & Astrophysics, 334, p. 713 – 728.